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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 : C03B 37/15 | A1

(11) International Publication Number: WO 99/23041

(43) International Publication Date: 14 May 1999 (14.05.99)

(21) International Application Number: PCT/US98/23003

(22) International Filing Date: 30 October 1998 (30.10.98)

(30) Priority Data:
60/063,830 30 October 1997 (30.10.97) US
09/182,056 29 October 1998 (29.10.98) US

(63) Related by Continuation (CON) or Continuation-in-Part (CIP) to Earlier Applications
US 60/063,830 (CON)
Filed on 30 October 1997 (30.10.97)
US 09/182,056 (CON)
Filed on 29 October 1998 (29.10.98)

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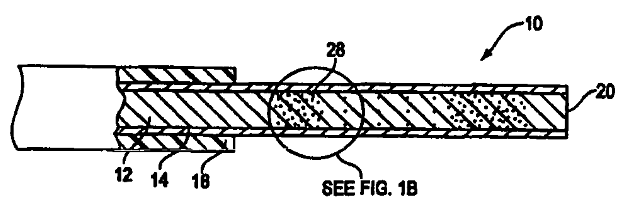
(81) Designated States: AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GE, GH, GM, HR, HU, ID, IL, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, UA, UG, US, UZ, VN, YU, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

Published
With international search report.
Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

(54) Title: FIBER OPTIC DIFFUSER AND METHOD OF MANUFACTURE

(57) Abstract

A fiber optic diffuser is disclosed in which the scattering elements are generated by an optical damage process to the core of an optical fiber. This eliminates the need to manufacture, and attach, a separate diffusing element. The location of the individual scattering elements can be selected arbitrarily, which allows diffusers with arbitrary irradiance distributions to be fabricated. A method of manufacturing the diffuser using a high power laser source is also disclosed.



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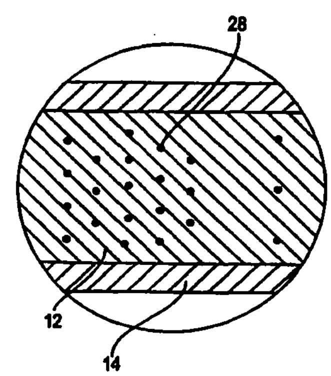

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FIBER OPTIC DIFFUSER AND METHOD OF MANUFACTURE

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to fiber optic diffusers and methods of manufacturing fiber optic diffusers.

2. Description of the Prior Art

The use of energy delivered from a light source, such as a laser, for medical applications is well documented. In certain biomedical applications, such as, for example, photodynamic therapy ("PDT"), optical waveguides (referred to herein as "optical fibers") are used to deliver light energy to internal areas of the human body not readily accessed directly by the light source and also to monitor the level of light in such areas. At the treatment site within the body the light may be used for photoablation, photocoagulation, to activate a photochemical drug, or to otherwise effectuate optically related treatments.

Optical fibers used in such therapies typically consist of an inner core having one index of refraction, surrounded by a cladding having a slightly lower index of refraction. Both the core and cladding may be comprised of either an optical glass or polymer (such as plastic). Light propagates down the optical fiber by means of total internal reflection at the

interface between the inner core and the cladding. The optical fiber is terminated at its distal end with a diffuser having an irradiance distribution appropriate to the particular treatment protocol. An outer protective jacket often covers the optical fiber.

Alternatively, light can be delivered into the body using an optical waveguide that consists of a core region only and the waveguiding effect is provided by the interface between the core and the surrounding medium. This type of optical waveguide will also be referred to herein as an optical fiber.

One current approach to diffuser construction is to diffuse scattering elements in a clear material such as epoxy, often with a density gradient of scattering elements to achieve an irradiance pattern that is uniform along the length of the diffuser. One drawback of this approach is that the diffuser is constructed separately and then attached to the end of the fiber resulting in a difficult manufacturing process and decreased reliability. Another drawback is that it is difficult to shape the irradiance pattern significantly because it is difficult to arrange the scattering elements in a systematic manner. An additional drawback is that the attachment technique often results in a fiber optic diffuser with a maximum diameter that is greater than the diameter of the fiber.

Another current approach to diffuser construction is to modify the fiber itself to prevent the total internal reflection of light at the core-cladding interface. There are several ways this is accomplished. One way is to choose a ratio of the indices of refraction between the outer cladding and the core region of the optical fiber so that internal reflection within the core region is substantially less than total. This causes light to radiate outward through the side of the core region and to emerge through (a preferably transparent) cladding. Another way is to alter the interface between the fiber optic core and cladding to increase side

radiation. Texturing the outer surface of the core region to provide a ground glass effect is one method commonly used. Another is to position or embed light scattering elements such as tiny particles at the surface of the fiber optic core near the interface with the cladding. Light scattering particles can also be imbedded throughout the cladding to enhance the side delivery of radiation. Yet another approach is to melt or otherwise deform the distal end of the fiber to reduce the waveguiding effect and thereby allow light to be emitted along the deformed region.

Current approaches that modify the fiber itself have only a limited capability to tailor the irradiance distribution. Diffusers which rely on mechanical alteration of the core-to-cladding interface or use a deformed distal end also have the drawback of potentially weakening the fiber mechanically. Moreover, removal of the cladding can also leave the core of the fiber exposed to chemical degradation.

SUMMARY OF THE INVENTION

It is an objective of the present invention to provide improved optical fiber diffusers for use in biomedical applications requiring light delivery, the diffusers having irradiance distributions tailored to particular treatment protocols, thus maximizing the therapeutic benefits of treatment, allowing the delivery of light to be better controlled, and reducing the unwanted side effects of treatment. The light diffusion mechanism of the present invention comprises scattering elements "written" directly into the core of an optical fiber using pulsed lasers with pulses that have relatively high peak powers (referred to herein as high power lasers).

It is a further object of the invention to provide optical fiber diffusers having diameters as small as the optical fiber diameter to reduce the overall profile, which is advantageous for catheter applications.

It is a further object of the invention to provide methods of manufacturing the improved diffusers that permit tailoring of the irradiance distributions during manufacture.

It is a further object of the invention to provide methods of manufacture wherein diffusers are formed internally within optical fibers, thus eliminating the need for separate mechanical attachment of the diffusers to the optical fibers, reducing the number of manufacturing steps required, and thereby reducing expense and improving reliability.

These and other objects are met by the present invention which includes a method of diffusing light from an optical waveguide (such as, for example, a glass body, a polymer, or other medium capable of transmitting light) by first focusing a relatively strong laser beam to a point within the waveguide so as to heat a small region within the waveguide and thereby permanently modify the small region's microscopic structure. After the small region within the waveguide is allowed to cool, a light source may then be applied to the waveguide so that the modified microscopic structure of the waveguide will cause at least some of the applied light to be scattered. The laser beam may preferably be focused to a point within the core through the cladding surrounding the core.

In one embodiment of the present invention, the light is focused into the optical waveguide's core from the distal end when the waveguide is surrounded by air. Alternatively, in a preferred embodiment, the waveguide is immersed in a liquid having an index of refraction substantially matching the index of refraction of the waveguide at its

surface. This reduces the reflection of light at the surface of the waveguide and allows light to be more properly focused within the waveguide. This allows for more well-defined scattering centers to be formed within the waveguide.

The method of the present invention may be used to form a fiber optic diffuser comprising an optical fiber having a core, a cladding, and, if required, a protective jacket. The distal end of the core preferably has at least one internal scattering element comprising a small region having optically induced changes to the microscopic structure of the region. The proximal end of the optical fiber is preferably adapted for coupling to a source of optical radiation and at least one internal scattering element directs a portion of the coupled optical radiation outwardly from the diffuser. The internal scattering elements may preferably be dispersed along the axial length of the diffuser, and the distribution may generally increase in a direction from the proximal end of the diffuser to the distal end of the diffuser. Alternatively, the distribution of scattering elements may be selected to provide a substantially uniform axial distribution of optical radiation over the length of the fiber optic diffuser. Alternatively, the location of the scattering centers can be such that arbitrary diffuser output profiles can be achieved. The diffused optical radiation may preferably be used to activate a photochemical drug and the distribution of scattering elements is preferably tailored to a particular treatment protocol.

The present invention also includes an automated process for manufacturing a fiber optic diffuser within an optical fiber, wherein the optical fiber has a core surrounded by a cladding. Preferably, the automated process includes the steps of focusing light from a writing laser having a first wavelength to a small region within the core of the distal end of the fiber so as to heat the small region, causing the microscopic structure of the small region

to be permanently modified; applying a light emission source having a second wavelength to the proximal end of the optical fiber so as to cause light to be scattered by the small region; testing the light of the second wavelength that is diffused from the optical fiber core with a test means that selectively measures light of the second wavelength; and concurrently adjusting the operation of the writing laser so that light of the second wavelength that is diffused from the optical fiber core meets a desired standard.

In another embodiment, the presently preferred invention includes an apparatus for producing a fiber optic diffuser formed from an optical fiber having a core and a cladding. The apparatus preferably includes a high power writing laser capable of emitting a relatively strong laser beam and an optical lens for focusing the emitted laser beam on a focal point within the core of the optical fiber such that the focused laser beam is capable of heating a small region within the core near the focal point and thereby permanently modify the small region's microscopic structure. The focal point within the core of the optical fiber may be adjusted to any arbitrary position along the length of the optical fiber. Preferably, the apparatus may also include a holding tank for holding a liquid having an index of refraction substantially matching index of refraction of the optical fiber at its surface. Using this holding tank, the emitted laser beam is preferably focused on a focal point within the core of the optical fiber within the holding tank.

The present invention also includes a method of phototherapy by placing a fiber optic diffuser in proximity to a treatment site, the diffuser comprising a core surrounded by a cladding and having a proximal end adapted for coupling to a source of therapeutic optical radiation and a distal end for diffusing the optical radiation outwardly, the distal end containing a plurality of light scattering elements distributed therein, with each scattering

element comprising a small region of material having optically induced changes to the local structure of the material. At least one source of therapeutic optical radiation is then applied to the proximal end of the fiber optic diffuser to effect treatment with the radiation diffused from the distal end of the diffuser.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention is further described in connection with the accompanying drawings, in which:

Figure la is a partial cutaway view of the optical fiber diffuser;

Figure 1b is a detail view showing the diffusion elements within the core of the optical fiber;

Figure 2 illustrates how diffusion elements within the optical fiber core are created using a high-power writing laser and focusing optics, focusing through the optical fiber cladding;

Figure 3 illustrates how diffusion elements within the optical fiber core are created using a high-power writing laser and focusing optics, focusing from the distal end of the optical fiber;

Figure 4 illustrates how the level of diffusion resulting from the diffusion zones within the optical fiber core can be tested using a test laser and light measurement apparatus;

Figure 5 illustrates how an arbitrary irradiance distribution can be created, with the light intensity varying along the length of the diffuser, allowing diffusers to be tailored to particular treatment protocols;

Figure 6 illustrates the manufacturing method of the present invention as incorporated into an automated system;

Figure 7 is a partial cutaway view of an alternative embodiment of the optical fiber diffuser of the present invention;

Figure 8 is a graphical representation of light radiation as a function of axial position along an optical fiber diffuser manufactured in accordance with one embodiment of the present invention;

Figure 9 is a graphical representation of light radiation as a function of axial position along an optical fiber diffuser manufactured in accordance with another embodiment of the present invention;

Figure 10a illustrates an optical fiber showing light reflecting off the outer surface of the fiber;

Figure 10b illustrates an alternative embodiment of the present invention in which the scattering centers are formed within the core of an optical fiber as the optical fiber is immersed in a liquid;

Figure 11a illustrates the length of an optical fiber diffuser that may be formed using one embodiment of the present invention;

Figure 11b illustrates another embodiment of the present invention in which a hole is formed in the focusing lens, thus increasing the length of the fiber optic diffuser that may be produced in accordance with the present invention; and

Figure 12 illustrates one preferred manufacturing assembly for producing optical fiber diffusers in accordance with the present invention.

These drawings are provided for illustrative purposes only and should not be used to unduly limit the scope of the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

As shown in Figures 1a and 1b, the optical fiber diffuser **10** of the present invention is fabricated from a standard optical fiber, which typically includes a core **12**, surrounded by a cladding **14**, which may be surrounded by a jacket **16**. An optical fiber diffuser **10** may be used, for example, in photodynamic therapies or other therapies involving the application of light. The core **12** of the optical fiber diffuser **10** may be formed from glass, polymers (such as plastic), or any other suitable medium capable of transmitting light. Although the optical fiber diffuser **10** illustrated in Figure 1 has had the jacket **16** of the optical fiber removed from the distal end **20** of the fiber, the present invention may be used with optical fibers without first removing their associated jackets **16**, provided that the jacket **16** sufficiently allows light to penetrate and pass through to the core **12**. The core **12** of the fiber has been modified with the creation of multiple small scattering centers **28** in the structure of the core **12** of the optical fiber. The scattering centers **28** (i.e., elements) consist of small regions of optically-damaged core **12** (i.e., glass or plastic for polymer fibers), which result in a permanent modification to the microscopic structure of the small regions of the core **12**.

In the fabrication method of the present invention (Figures 2 and 3), the diffuser is formed within the distal end **20** of the optical fiber itself. As can be appreciated by those skilled in the art, the diffuser may be formed in any arbitrary region of the optical fiber. An intense light from a high-power writing laser **40** is focused with focusing optics **50** to a

small point within the core **12** of the optical fiber, creating a small area of optically induced damage. A short pulse of light from the high-power writing laser **40** imparts sufficient energy to the focal point within the fiber core that the core material at the small region near the focal point is changed (i.e., optically induced damage). These changes are generally thought to be a result of initial melting followed by rapid cooling after the pulse has passed. With this rapid cooling the material returns to its solid state leaving a local discontinuity between the melted volume and the surrounding material. These local discontinuities between the bulk core material and the optically damaged regions have the useful characteristic of scattering light, thus functioning as scattering centers **28** within the optical fiber core **12**.

A diffuser having a specifically tailored irradiance distribution is manufactured by forming numerous scattering centers **28** within the optical fiber core **12**. For each scattering center the relative positions of the fiber and the focusing optics are changed, moving the focal region to a different point in the fiber, where another scattering center is to be created. This process is repeated until all individual scattering centers have been created, thereby forming the diffuser within the fiber.

The light from the high-power writing laser **40** and focusing optics **50** can be focused on a point within the core **12** either through the cladding **14** from the side, as shown in Figure 2, or from the distal end **20** of the fiber, as shown in Figure 3. Although one writing laser is shown, multiple lasers (not shown) may also be used, operating either at the same or different wavelengths, to achieve the required effect; the focusing optics thus may comprise multiple sets of optics (not shown). The writing laser **40** is preferably capable of emitting a beam of relatively strong pulses or an externally modulated, relatively high power beam.

During manufacture of the diffuser, the irradiance distribution being created may be measured using an emission source **60** attached to the proximal end of the optical fiber (Figure 4). In this invention the distal end is used to refer to the end of the optical fiber at which the diffuser is located and the proximal end refers to the opposite end of the fiber. The emission source transmits light down the fiber which is diffused by the scattering centers **28**, and which is then detected and quantified by an optical output detector **70**.

A similar technique can be used to monitor the formation of scattering centers. Once a scattering center is formed, it scatters light from the pump laser along the direction of the optical axis. The result is a significant change in the amount of pump light that is detected at either end of the optical fiber. Monitoring changes in the amount of this light that is coupled into the fiber core modes allows one to detect when a scattering center is formed.

It is envisaged that diffuser emission profiles can be tailored to provide non-uniform or customized output profiles. Figure 5 shows a diffuser that has been formed by creating a relatively high population of scattering centers **28** (or scattering centers **28** of relatively large size) near the distal end of the fiber, a region having a lower density of scattering centers **28** (or scattering centers **28** of relatively small size) proximal to this region, and then high density region of scattering centers **28** (or scattering centers **28** of relatively large size) proximal to this region. The effect of such a population of damage sites on the diffuser optical output profile is illustrated in Figure 5b, which illustrates the diffuser's output power as a function of the distance along the diffusing element. The scattered intensity will be high near the regions with high densities of scattering centers **28** (or scattering centers **28** of relatively large size), then lower near the region of fewer scattering centers **28**, then higher near the region of high densities of scattering centers **28**.

In order to achieve a uniform output intensity along the length of the diffuser, it is necessary to have the amount of scattering increase from the proximal toward the distal end of the fiber, because there is less light available at the distal end and, therefore, more scattering is necessary as the light travels to distal end of the fiber. To achieve non-uniform light output will require similar considerations in locating the scattering centers or the distribution of scattering. The current technique is especially suited for addressing these concerns as it allows the scattering centers and their size to be located in an arbitrary, predefined manner.

It is envisaged that diffuser emission profiles can also be tailored to specific treatment sites. For example, diffusers can be manufactured in such a way that their emissions will possess an inverted triangle profile appropriate to treating the uterus; in other applications where body cavities possess complex shapes requiring a sculptured emission profile, the diffuser can be fabricated to match the required profile. Customized emission profiles could also be created by scanning a tumor prior to treatment and then sculpting the diffuser to emit a profile which fills the tumor completely while emitting little light into non-tumor tissue. A similar approach would allow custom fibers to be used to fill the prostate or other glands while avoiding spilling light into adjacent tissue and thus again containing the PDT effect within the target tissue.

Although described in the context of conventional optical fibers, the present invention can also be applied to non-conventional waveguides, such as a solid glass or plastic rod of a diameter significantly larger than is typical of conventional optical fibers. Such a light diffusing wand could also be used to deliver diffusive light to areas of the body that have sufficiently large openings to be easily accessed. Examples would include

gynecological applications, adjunctive treatment associated with brain tumor surgery, light treatment of lesions in the oral cavity, and light treatment of the colon.

In an automated manufacturing process, the fabrication of the diffuser may be computer controlled for improved manufacturability using techniques well-known in the art. As illustrated in Figure 6, the optical fiber is connected at its proximal end to the emission source **60** throughout the process of creating the scattering centers. The writing laser operates at a different wavelength (λ_1) than the emission source (λ_2). Optical filters **80** which selectively block light at λ_1 but transmit light at λ_2 protect the emission source **60** and the optical output detector **70** from the power of the writing laser. The writing laser, optical output detector, and the positioning system (not shown) for controlling relative positions of the writing laser, optical fiber, and optical output detector may all be under the control of a computer (not shown). Feedback within the control software permits precise tailoring of the irradiance distribution. Variations well-known in the art to the manufacturing process are possible; for example, the optical filters **80** may be omitted and mechanical or optical blockers (not shown) used to protect the emission source **60** and the optical output detector **70** during firing of the writing laser, in which case the writing laser and emission source may operate at the same wavelength.

An alternative form of the optical fiber diffuser of the present invention is shown in Figure 7. In this alternative form, the outer jacket **16** of the optical fiber is left intact over the entire optical fiber. The outer jacket comprises an optically transparent material such as a transparent plastic. During fabrication of the diffuser, light from the writing laser **40** and focusing optics **50** may be focused through both the transparent outer jacket **16** and the cladding **14** to the core of the fiber **12**. The light from the writing laser is

unfocused as it passes through the outer jacket, thus allowing fabrication of scattering centers within the core of the fiber without damage to the outer jacket. Alternatively, scattering centers may be created within the core of the fiber from the distal end **20** of the fiber. In testing and use of the diffuser of the alternate embodiment, light from an emission source at the proximal end of the optical fiber is diffused by the scattering centers and passes unimpeded through the transparent outer jacket. The intact outer jacket of the alternate embodiment provides both mechanical and chemical protection to the optical fiber.

An experimental demonstration of one preferred embodiment of the present invention was performed using a pulsed laser operated in both single shot mode and at low repetition rate (5 Hz). The writing beam used a wavelength of 532 nanometers with 30 picosecond pulses having energies ranging from 60 microjoules to 175 microjoules. This beam was focused into an optical fiber from the side as illustrated in Figure 6. In this demonstration the jacket **16** was stripped from the fiber and the fiber was mounted on a three-axis translation stage having the additional capability to adjust pitch and yaw. Using these mechanical adjustments, the fiber was aligned such that it could be translated along its optical axis, always keeping the focused spot located at the fiber core. Using this technique, several diffusers were fabricated.

In one of these cases, the pulse energy of the writing laser **40** was set at 125 microjoules and the laser was operating at a 5 Hz repetition rate. The output of a low-power helium-neon laser operating at 633 nm was directed into the proximal end of the fiber such that the buildup of scattering centers could be monitored at the distal end. In this case, rather than using the detector shown in Figure 6, the development of scattering centers was monitored by viewing the distal end through a pair of laser safety glasses that blocked the 532

nm beam. With the relative positions of the fiber and writing laser **40** held fixed, the distal end of the fiber was observed and as soon as a scattering center began to develop, i.e., as soon as a red spot began to develop within the fiber, the fiber was translated such that the writing laser **40** was then focused on a fresh spot within the fiber and the process repeated. In practice, the result was a nearly continuous back and forth translation of the fiber along its optical axis while the writing laser was running continuously at 5 Hz.

As is known, the focused spot of a laser beam is elliptical rather than spherical, with the major axis of the ellipse parallel to the optical axis of the beam. For the above experiment, this results in elliptical scattering centers that are aligned along the optical axis of the writing laser beam, and are perpendicular to the optical axis of the fiber. To increase the amount of scattering, the fiber was rotated 90 degrees around its optical axis, with the above procedure repeated with the fiber in this orientation. Using this technique, elliptical scattering centers with their optical axes oriented at 90 degrees to each other within the core of the fiber may be created.

To quantify the nature of the diffuser created in the above procedure, the diffusing portion of the optical fiber was placed in front of a Spiricon® laser beam analyzer oriented such that the diffuser was viewed from the side. With the fiber oriented in this position, the proximal (opposite) end of the fiber was connected to a Miravant™ laser (DD2 Model). The resulting intensity profile is illustrated in Figure 8. As shown by the figure, this type of scattering center density and size results in a diffuser with an output light distribution that is strongest near the proximal end of the diffuser.

The present invention may also be used to create optical fiber diffusers having arbitrary non-uniform diffuser outputs. As an illustration of this embodiment, another fiber

was mounted as above, except in this case the laser pulse energy was increased to approximately 175 microjoules. At this energy, a sufficient amount of damage is induced with a single pulse to result in significant scattering of light from the writing laser **60**. Multiple shots from the writing laser **60** on a single focus spot resulted in increasing the amount of scattering from that spot, as a result of increasing the size of the damage spot. To take advantage of this, the focus spot of the writing beam was situated near the distal end of the fiber and that spot was irradiated with 20 pulses from the writing laser **60**. The optical fiber was then moved 0.0125 inches along its optical axis so that the beam of the writing laser **60** would be focused at a new spot located 0.0125 inches proximal to the previous spot. The laser **60** was then turned on for 20 shots and a new damage spot was created. This process was repeated until damage spots had been written along the distal 2 cm length of the optical fiber. At that point, this same process was continued except the scattering centers were spaced 0.025 inches apart. The result is a 2 cm section at the distal end containing scattering centers spaced 0.0125 inches apart. Proximal to that is similar diffuser section, also 2 cm long, only with scattering centers spaced 0.025 inches apart. This results in a very simple non-uniform population of scattering centers. The diffuser's optical output measured using the above Spiricon® assembly is illustrated in Figure 9. As illustrated in Figure 9, this simple non-uniform distribution of scattering centers results in a more uniform light output of the diffuser as would be expected. The strong output peak at the distal end of the diffuser is most likely due to scattering from the end of the fiber and is an indication that only a fraction of the total light is scattered out of the optical fiber by the diffusing centers.

The above experiments demonstrate the fundamental feasibility of this concept. Although these demonstrations use a side-firing arrangement for the writing fiber,

an unjacketed fiber, a specific pulse energy, a specific wavelength, a specific optical focusing scheme, and a specific scheme for monitoring the formation of the scattering centers, these may all be varied and the resulting technique will still be within the spirit and scope of the present invention.

The present invention also includes a method to overcome the difficulty in focusing the writing beam into the optical fiber to create scattering centers. This is primarily a result of the fact that light is reflected off the outer surface of the fiber as illustrated in Figure 10a. This outer surface could be the core of the optical fiber, the cladding surrounding the core, or even the protective jacket. This reflection is due to the relatively large difference in refractive index between the outer surface and the air surrounding it. To minimize this problem, as shown in Figure 10b, the fiber can be placed in a liquid **80** (e.g., water) such that the refractive index difference is reduced and the resulting reflection of the writing beam light at the outer surface of the fiber is substantially reduced. Preferably, the index of refraction of the liquid **80** is selected to substantially match the index of refraction at the surface of the optical fiber.

The present invention further includes a method and apparatus to produce optical fiber diffusers of arbitrary length having scattering centers located in any arbitrary position along the core of the optical fiber. The basic arrangement illustrated in Figure 3 shows that the length of the diffuser that can be constructed is generally limited to the focal length of the lens **50**. For diffusers longer than this, the distal end of the fiber runs into the surface of the lens **50** as illustrated in Figure 11a. To eliminate this problem, a hole **52** may preferably be placed through the lens **50** to allow the fiber to pass through as illustrated in Figure 11b, thus allowing the fiber to pass through the lens **50** such that the focal point within

the core of the fiber may be adjusted to any arbitrary position along the length of the optical fiber.

Figure 12 illustrates one preferred diffuser fabrication assembly **90**. Preferably, the fabrication assembly includes a writing laser **40** that emits a laser beam **92**. The laser beam **92** is expanded and collimated through a set of lenses, **94a** and **94b**. The laser beam **92** is then re-positioned so that it is parallel to the axis of the optical fiber **120** using, for example, a set of mirrors **102** and **104**. The laser beam **92** then passes through an iris **98**, which attenuates the amount of light directed at the optical fiber **120** and modulates the diameter of the focused spot of the laser beam **92**. The laser beam **92** then passes through a focusing lens **110** and is focused into the core of the optical fiber **120**. Preferably, the optical fiber **120** is retained and translated along its optical axis using, for example, an independent linear stage **109** that positions the focused spot of the laser beam **92** relative to the distal end of the optical fiber **120**. The optical fiber **120** is held to this linear stage **109** using a holding fixture **108**. In order to keep the fiber aligned relative to the optical axis of the lens **110**, it is preferably passed through a fiber guide **111** that is held fixed to the optical mount that holds the lens **110**. In the configuration shown in Figure 12, the optical fiber **120** also passes through a hole in the mirror **104** to allow the linear stage **109** to be situated well outside the optical beam path. To reduce reflection of the writing laser beam at the fiber's surface, the fiber and is immersed into a liquid bath **100**, which contains liquid having an index of refraction substantially matching the index of refraction of the surface of the optical fiber **120**. Using this assembly, the laser beam **92** is focused into the liquid bath **100** and into a focal point within the core of the optical fiber **120**. The position of the focused spot in the plane transverse to the optical axis is controlled by adjusting the linear translation stages (not

shown). These translate the beam relative to the optical axis of the lens, thereby causing the focus spot to move within the transverse plane but not move substantially relative to the distal end of the fiber.

While the present invention is characterized as an optical fiber diffuser, it may also be used to detect light in treatment protocols using multiple optical fibers or separate sources of illumination. Further, the field of use of the present invention is not limited to biomedical applications, but includes all applications in which remote delivery or sensing of light is necessary or desirable. The method of creating light scattering centers within an optical fiber by optical damage is specifically not limited to conventional optical fibers, but may be applied to any optically transparent material where the inclusion of scattering centers is desired for light diffusion or detection.

The above is a detailed description of particular embodiments of the invention. It is recognized that departures from the disclosed embodiments may be within the scope of this invention and that obvious modifications will occur to a person skilled in the art. This specification should not be construed to unduly narrow the full scope of protection to which the invention is entitled.

CLAIMS

What is claimed is:

1. A method of diffusing light from a glass body, comprising the steps of:

a) focusing a relatively strong laser beam to a point within the glass body so as to heat a small region within the glass body and thereby permanently modify the small region's microscopic structure;

b) allowing the small region within the glass body to cool; and

c) applying a light source to the glass body so that the modified microscopic structure of the glass body will cause at least some of the applied light to be scattered.

2. The method of claim 1 wherein the glass body comprises a core surrounded by a cladding, the glass body having a proximal and a distal end.

3. The method of claim 2 wherein the laser beam is focused to a point within the core through the cladding.

4. The method of claim 2 wherein the laser beam is focused to a point within the core from the distal end of the glass body.

5. The method of claim 1 wherein the glass body has an outer surface having an index of refraction, the method further comprising the step of immersing the glass body in a

liquid having an index of refraction substantially matching the index of refraction of the outer surface prior to focusing the laser beam to a point within the glass body.

6. The method of claim 5 wherein the outer surface comprises either a core, a cladding surrounding the core, or a protective jacket surrounding the cladding.

7. A method of diffusing light from an optical waveguide having a guiding core comprising the steps of:

a) focusing a relatively strong laser beam to a point within the core of the waveguide to heat a focal region within the waveguide and thereby permanently modify the focal region's optical properties;

b) allowing the focal region to cool; and

c) applying a light source to the optical waveguide so that the modified structure of the waveguide will cause at least some of the applied light to be scattered.

8. The method of claim 7 wherein the guiding core is comprised of a transparent glass.

9. The method of claim 7 wherein the guiding core is comprised of a polymer.

10. The method of claim 7 wherein the optical waveguide further comprises a cladding surrounding the guiding core, and wherein the guiding core comprises a proximal and a distal end.

11. The method of claim 10 wherein the laser beam is focused to a point within the guiding core through the cladding.

12. The method of claim 10 wherein the laser beam is focused to a point within the guiding core from the distal end of the optical waveguide.

13. The method of claim 7 wherein the optical waveguide has an outer surface having an index of refraction, the method further comprising the step of immersing the optical waveguide in a liquid having an index of refraction substantially matching the index of refraction of the outer surface prior to focusing the laser beam to a point within the optical waveguide.

14. The method of claim 13 wherein the outer surface comprises either the guiding core, a cladding surrounding the guiding core, or a protective jacket surrounding the cladding.

15. A method of forming a fiber optic diffuser, the diffuser comprising an optical fiber having a core and a cladding, and having a proximal and a distal end, the method comprising the steps of:

a) arranging a writing laser with high peak power capable of emitting a laser beam;

b) arranging an optical lens for focusing the writing laser beam on a focal point within the core of the optical fiber;

c) emitting laser energy from the writing laser sufficient to heat a small region within the core near the focal point and thereby permanently modify the small region's microscopic structure; and

d) allowing the small region within the core to cool.

16. The method of claim 15 wherein the writing laser is capable of emitting a beam of relatively strong pulses or an externally modulated, relatively high power beam.

17. The method of claim 15 wherein the laser beam is focused to the focal point within the core through the cladding.

18. The method of claim 15 wherein the laser beam is focused to the focal point within the core from the distal end of the optical fiber.

19. The method of claim 15 wherein the optical fiber has an outer surface having an index of refraction, the method further comprising the step of immersing the optical fiber in a liquid having an index of refraction substantially matching the index of refraction of the outer surface prior to emitting the laser energy.

20. The method of claim 19 wherein the outer surface comprises either the core, the cladding, or a protective jacket surrounding the cladding.

21. The method of claim 15 further comprising the step of modifying the focal point of the focused writing laser beam to heat a subsequent small region within the core and thereby permanently modifying the subsequent small region's microscopic structure.

22. The method of claim 21 wherein the focal point of the focused writing laser beam is modified by moving the optical fiber along its optical axis.

23. The method of claim 21 wherein the focal point of the focused writing laser beam is modified by changing the relative position of the optical fiber and the focal point by moving either the optical fiber or the focal point along the optical axis of the optical fiber.

24. The method of claim 21 wherein the focal point of the focused writing laser beam is modified by changing the relative position of the optical fiber and the focal point by moving either the optical fiber or the focal point in a direction transverse to the optical axis of the optical fiber.

25. The method of claim 21 wherein the focal point of the focused writing laser beam is modified by rotating the optical fiber along its optical axis.

26. The method of claim 15 further comprising the step of applying a light source to the optical fiber so that the modified microscopic structure of the core will cause at least some of the applied light to be scattered.

27. The method of claim 26 further comprising the step of coupling an optical detector to the optical fiber to detect and quantify the amount of applied light scattered by the fiber optic diffuser.

28. A fiber optic diffuser comprising an optical fiber having a core and a cladding surrounding the core, and having a proximal end and a distal end, and in which the core at the distal end has at least one internal scattering element comprising a small region of the core having optically induced changes to the microscopic structure of the small region.

29. The fiber optic diffuser of claim 28 wherein the proximal end is adapted for coupling to a source of optical radiation and the at least one internal scattering element directs a portion of the coupled optical radiation outwardly from the diffuser.

30. The fiber optic diffuser of claim 29 wherein the at least one scattering element comprises a distribution of scattering elements along the axial length of the diffuser, and wherein the distribution of scattering elements generally increases in a direction from the proximal end of the diffuser to the distal end of the diffuser.

31. The fiber optic diffuser of claim 30 wherein the distribution of scattering elements is selected to provide a substantially uniform axial distribution of optical radiation over the length of the fiber optic diffuser.

32. The fiber optic diffuser of claim 30 wherein the distribution of scattering elements is arranged to provide an arbitrary, non-uniform optical output from the diffuser.

33. The fiber optic diffuser of claim 30 wherein the optical radiation is used to activate a photochemical drug and wherein the distribution of scattering elements is tailored to a particular treatment protocol.

34. The fiber optic diffuser of claim 30 wherein the optical radiation is used to deliver optical radiation for optically-based therapy.

35. The fiber optic diffuser of claim 28 wherein the diameter of the diffuser remains substantially constant over the length of the diffuser.

36. An optical transmission and diffusion device comprising a core surrounded by a cladding and having a proximal end adapted for coupling to a source of optical radiation and a distal end for directing optical radiation outwardly, the distal end comprising a plurality of light scattering elements distributed therein, each scattering element comprising a small region having optically induced changes to the microscopic structure of the region.

37. The optical transmission and diffusion device of claim 36 where each scattering element directs optical radiation entering the proximal end outward from the distal end of the device.

38. The optical transmission and diffusion device of claim 36 wherein the distribution of scattering elements is selected to provide a substantially uniform axial distribution of optical radiation over the distal end of the optical transmission and diffusion device.

39. The optical transmission and diffusion device of claim 36 wherein the distribution of scattering elements generally increases along the distal end of the optical transmission and diffusion device.

40. The fiber optic diffuser of claim 36 wherein the distribution of scattering elements is arranged to provide an arbitrary, non-uniform optical output from the diffuser.

41. The optical transmission and diffusion device of claim 36 wherein the optical radiation is used to activate a photochemical drug and wherein the distribution of scattering elements is tailored to a particular treatment protocol.

42. The fiber optic diffuser of claim 36 wherein the optical radiation is used to deliver optical radiation for optically-based therapy.

43. The optical transmission and diffusion device of claim 36 wherein the diameter of the device remains substantially constant over the length of the optical transmission and diffusion device.

44. An automated process for manufacturing a fiber optic diffuser within an optical fiber, the optical fiber having a core and a cladding, and having a proximal end and a distal end, the process comprising the steps of:

a) focusing light from a writing laser having a first wavelength to a small region within the core of the distal end of the fiber so as to heat the small region, causing the microscopic structure of the small region to be permanently modified;

b) applying a light emission source having a second wavelength to the proximal end of the optical fiber so as to cause light to be scattered by the small region;

c) testing the light of the second wavelength that is diffused from the optical fiber core with a test means that selectively measures light of the second wavelength; and

d) concurrently adjusting the operation of the writing laser so that light of the second wavelength that is diffused from the optical fiber core meets a desired standard.

45. An automated process for manufacturing a fiber optic diffuser within an optical fiber, the optical fiber having a core and a cladding, and having a proximal end and a distal end, the process comprising the steps of:

a) focusing light from a writing laser having a first wavelength to a small region within the core of the distal end of the fiber so as to heat the small region, causing the microscopic structure of the small region to be permanently modified;

b) repeating step a) at different small regions within the core to provide a predetermined spatial population of scattering centers within the core.

46. An apparatus for forming a fiber optic diffuser, the diffuser comprising an optical fiber having a core and a cladding, and having a proximal and a distal end, the apparatus comprising:

a high power writing laser capable of emitting a relatively strong laser beam;

an optical means for focusing the emitted laser beam on a focal point within the core of the optical fiber such that the focused laser beam is capable of heating a small region within the core near the focal point and thereby permanently modify the small region's microscopic structure.

47. The apparatus of claim 46 wherein the optical means comprises a lens, the lens comprising means for allowing the optical fiber to pass through the lens such that the focal point within the core of the optical fiber may be adjusted to any arbitrary position along the length of the optical fiber.

48. The apparatus of claim 46 wherein the optical fiber has an outer surface having an index of refraction, the apparatus further comprising a means for holding a liquid having an index of refraction substantially matching the index of refraction of the outer surface, and wherein the emitted laser beam is focused on a focal point within the core of the optical fiber within the means for holding a liquid.

49. The apparatus of claim 48 wherein the outer surface comprises either the core, the cladding, or a protective jacket surrounding the cladding.

50. A method of phototherapy comprising the steps of:

a) placing a fiber optic diffuser in proximity to a treatment site, the diffuser comprising a core and having a proximal end adapted for coupling to a source of therapeutic optical radiation and a distal end for diffusing the optical radiation outwardly, the distal end comprising a plurality of light scattering elements distributed therein, each scattering element comprising a small region of material having optically induced changes to the local structure of the material;

b) providing at least one source of therapeutic optical radiation to the proximal end of the fiber optic diffuser; and

c) activating the source of therapeutic optical radiation to effect treatment with diffused radiation.

51. The method of claim 50 wherein the diffuser further comprises a cladding surrounding the core.

52. The method of claim 51 wherein the diffuser further comprises a protective jacket surrounding the cladding.

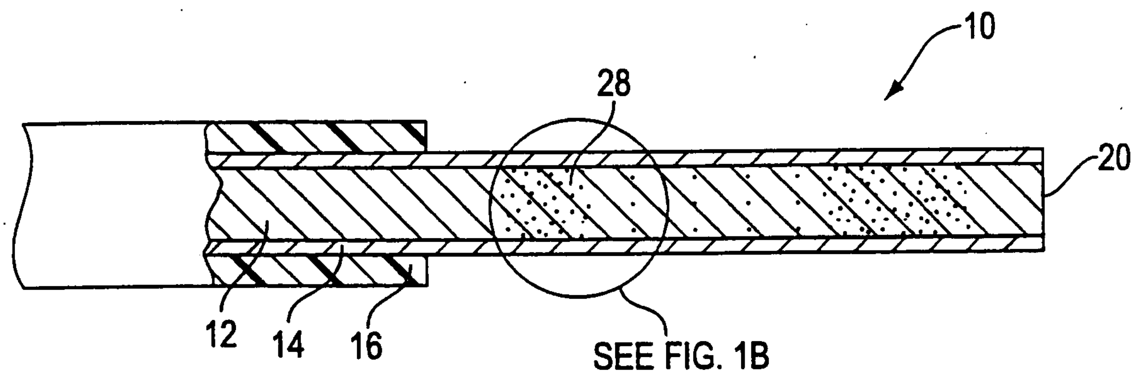


FIG. 1A

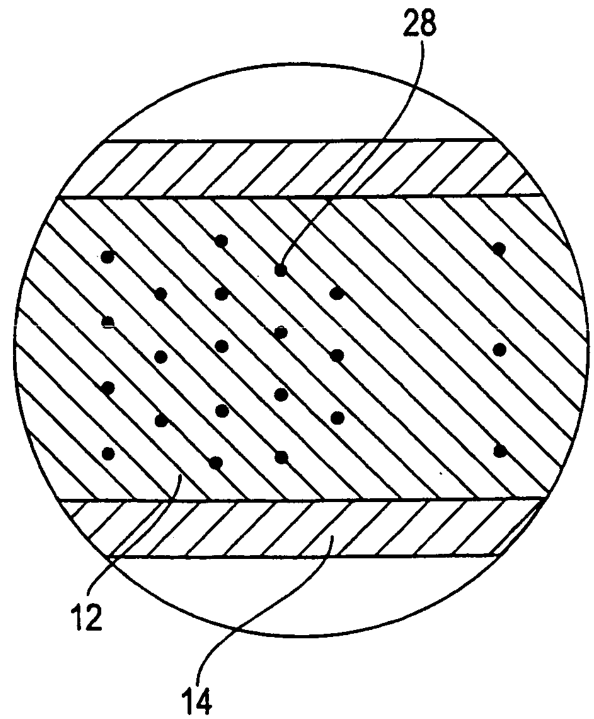


FIG. 1B

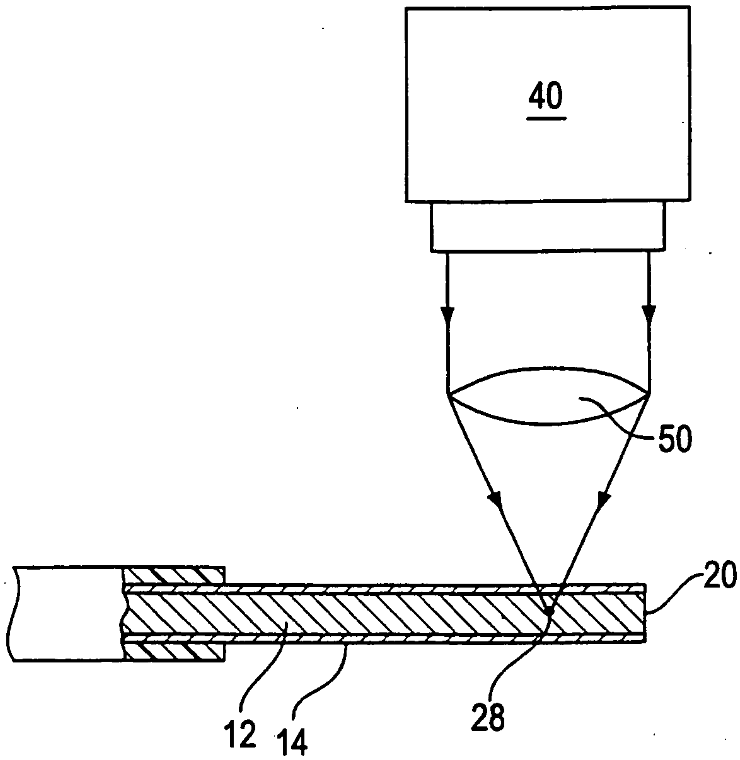


FIG. 2

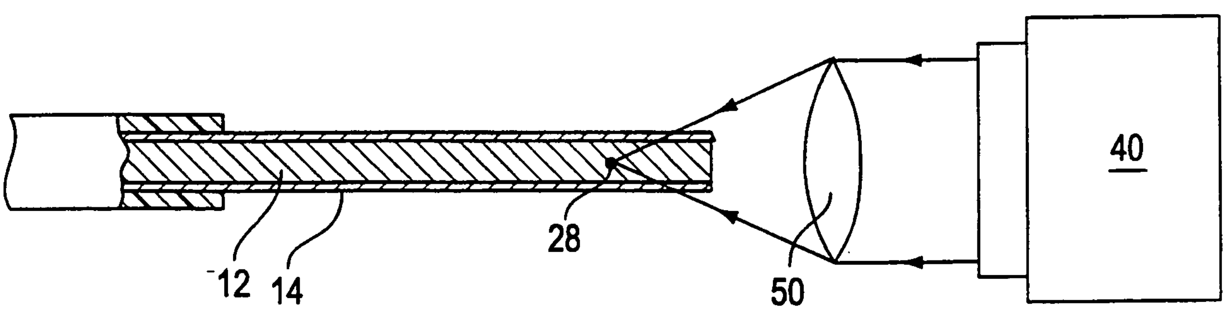


FIG. 3

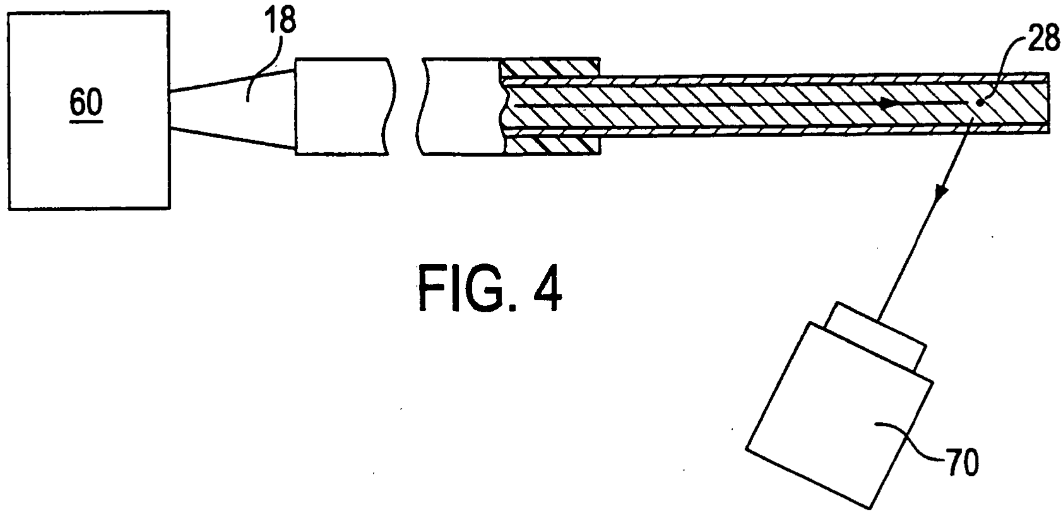


FIG. 4

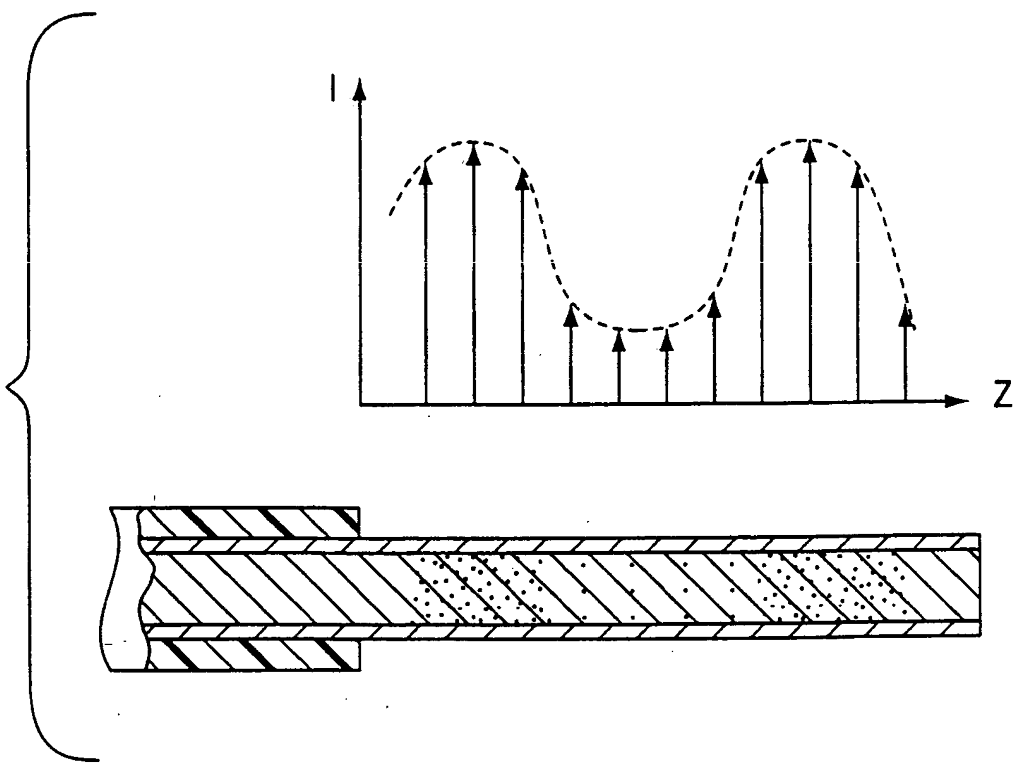


FIG. 5

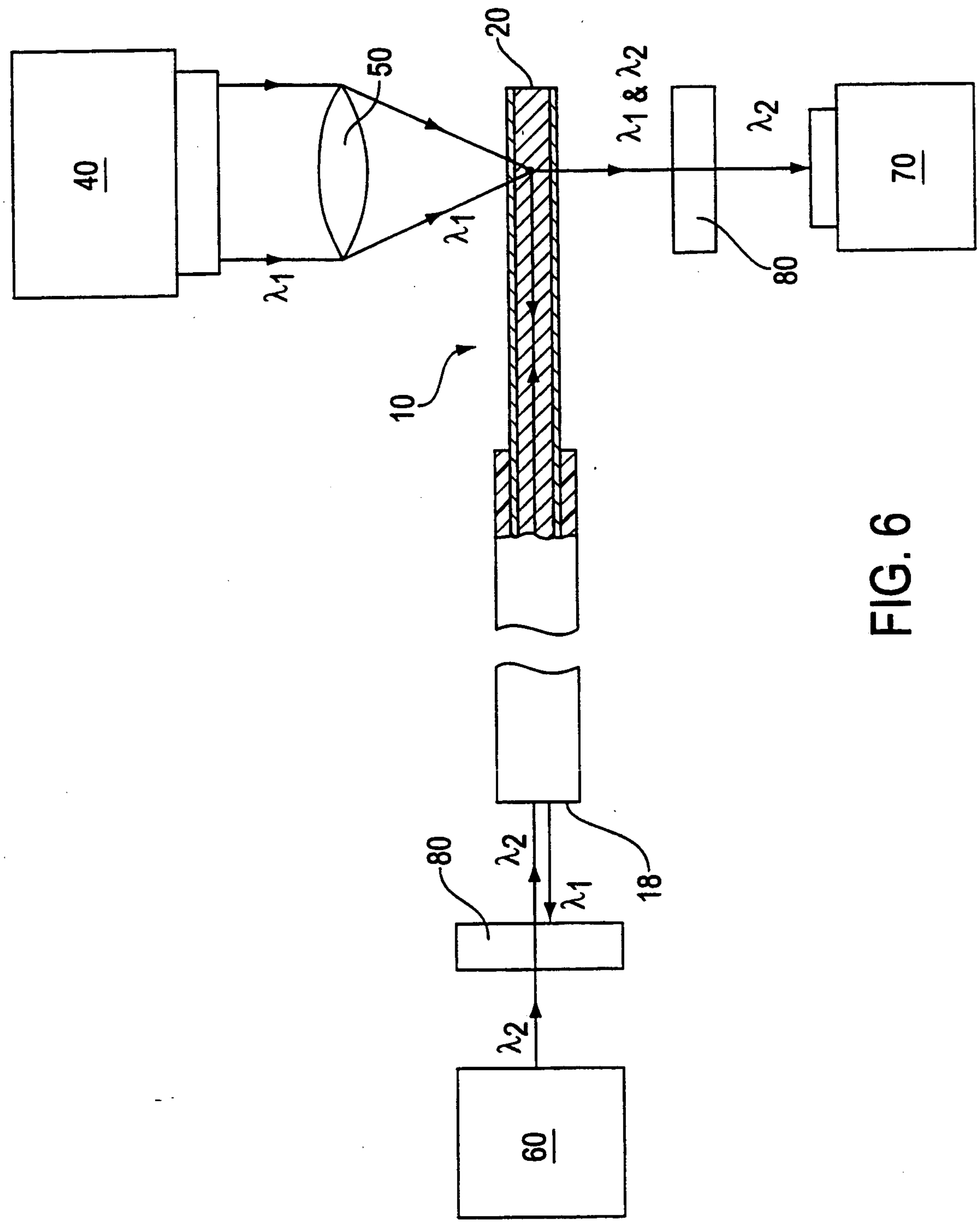

40
50
20
λ_1 & λ_2
λ_2
70
λ_1
λ_1
80
10
18
80
λ_2
λ_1
λ_2
60

FIG. 6

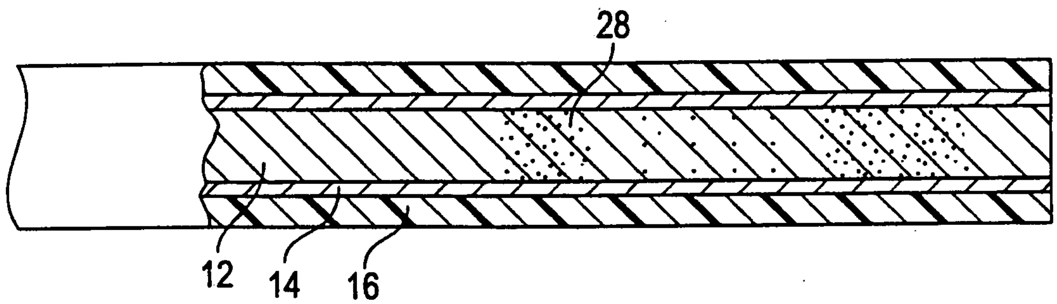
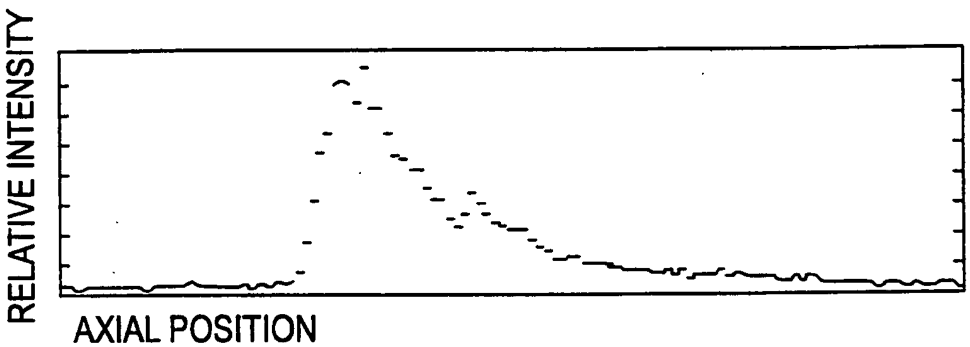
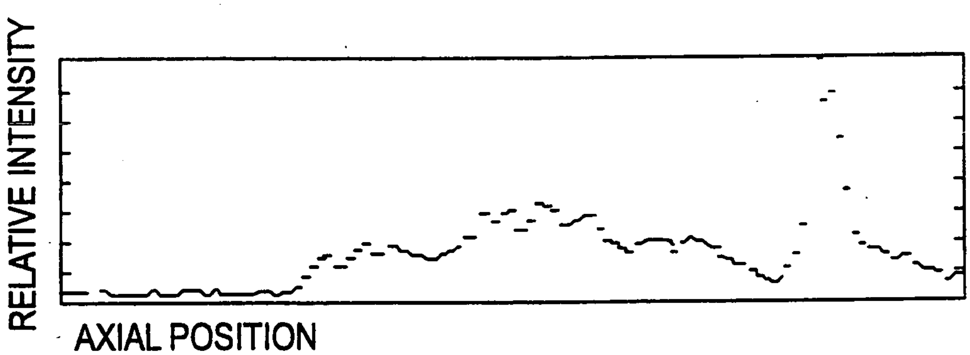


FIG. 7



RELATIVE INTENSITY
AXIAL POSITION

FIG. 8



RELATIVE INTENSITY
AXIAL POSITION

FIG. 9

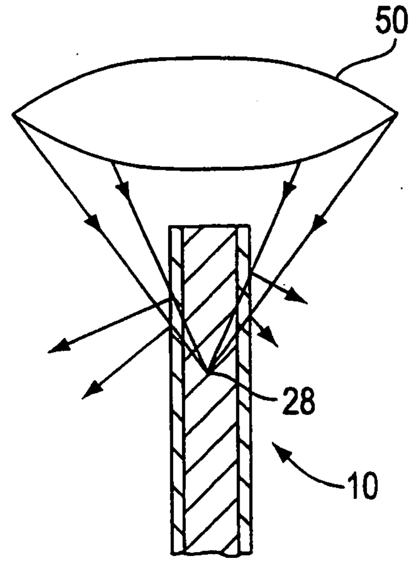


FIG. 10A

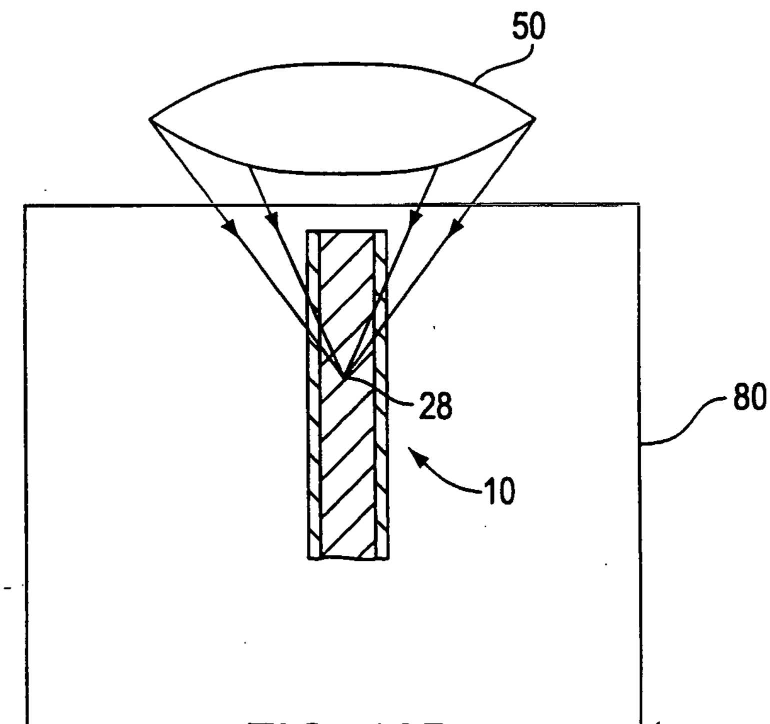


FIG. 10B

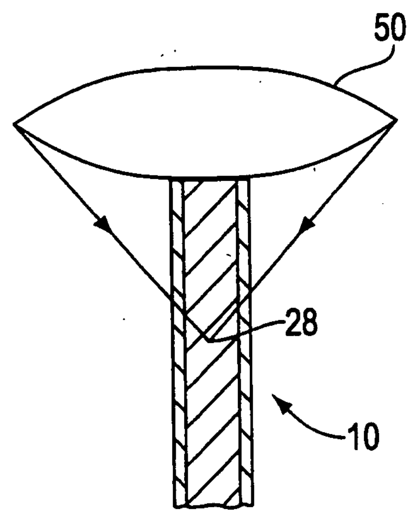


FIG. 11A

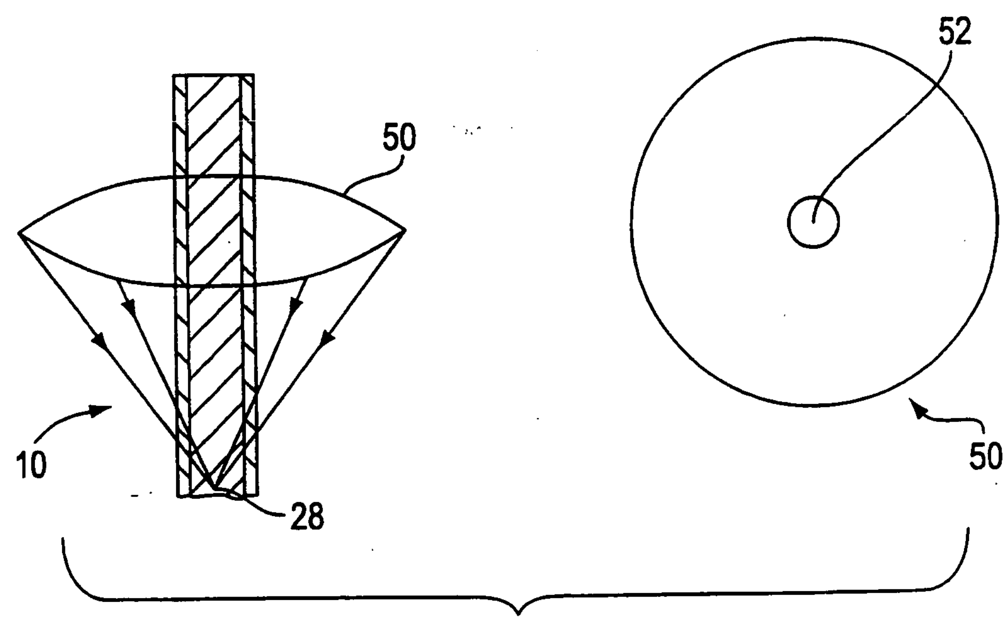


FIG. 11B

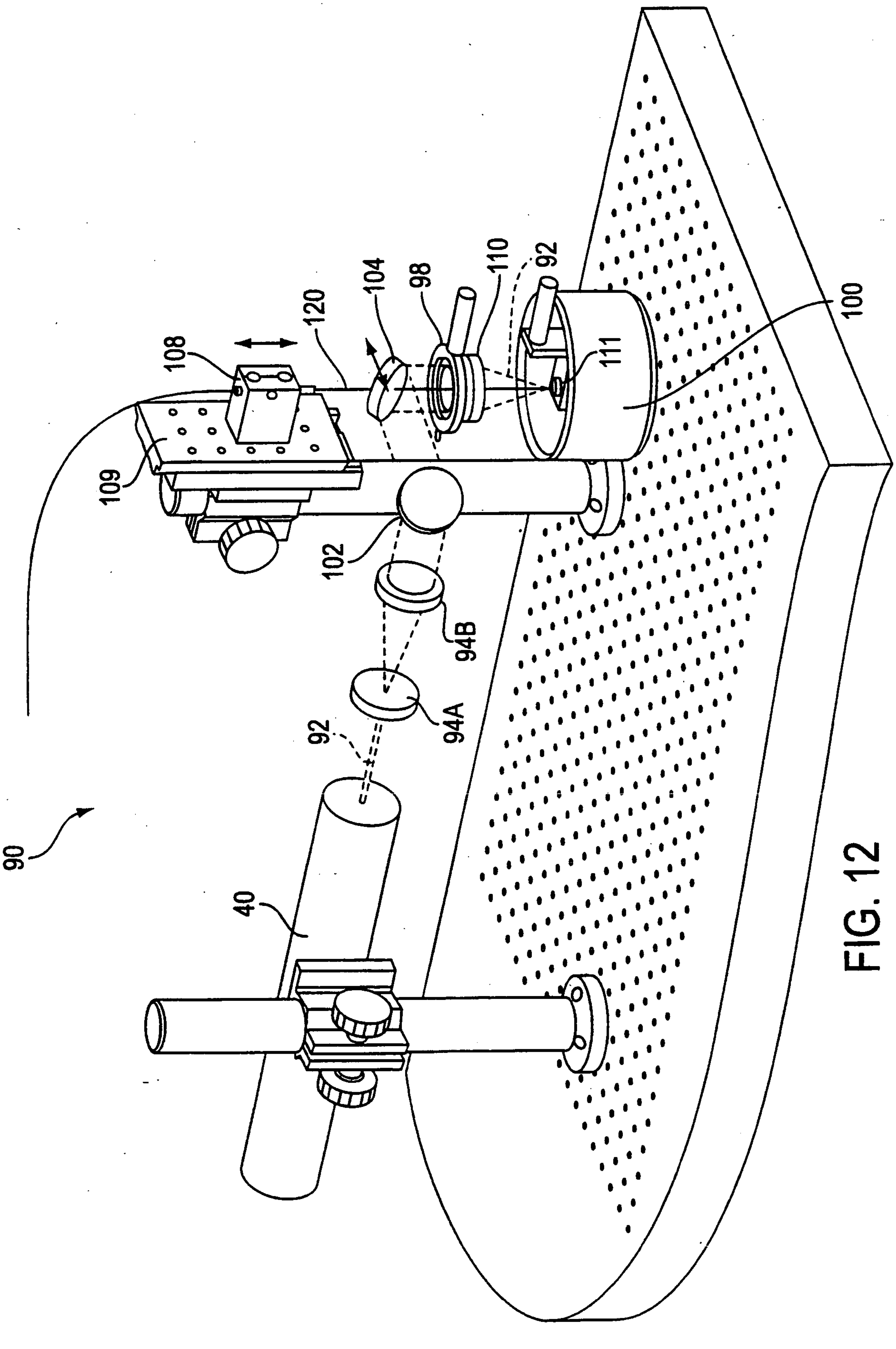


FIG. 12

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 98/23003

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 C03B37/15

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 C03B G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 0 309 234 A (BRITISH TELECOMMUNICATIONS) 29 March 1989 see the whole document -----	1-52

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
22 February 1999	01/03/1999

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Van den Bossche, W

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INTERNATIONAL SEARCH REPORT

Info...ation on patent family members

Internati Application No
PCT/US 98/23003

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